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DEVELOPMENT OF A NEW TYPE OF ICE SLURRY GENERATOR

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ABSTRACT

This paper describes a new type of ice slurry generator based on a little known phenomenon called "water supercooling". The main characteristic of such a machine is its capability to generate a continuous flow of supercooled liquid water (at about -2 °C) which can be made to partially change phase when and where desired, for example in a storage tank. The method has already been described in two previous publications and results of tests performed on a small laboratory model were then presented. The technology has very good potential for district heating and cooling as well as in a number of other fields. The present paper also gives the results of a series of tests performed on a transportable demonstration unit capable of generating 2 tons of ice per day. The unit has performed very well, results being sometimes above our most optimistic expectations. For example, it was found that the machine could generate ice slurries from just about any type of water, from the pure and highly filtered water to the very polluted or saline water. It is also possible to vary the size of the ice crystals generated; such a capability could be important in some applications such as water purification. The name given to this new technology is SUPERPAC (for: SUPER Pompe A Chaleur, or super heat pump) .

Keywords

Ice slurry, heat pump, ice-making heat pump, chiller, ice, ice crystal, heating, cooling, district heating, district cooling.

INTRODUCTION

The idea for this new technology began to take shape 8 years ago in Laval University's engineering building, in a laboratory named EDEN, where research was being done for the purpose of finding a simpler and more efficient heating system. After a detailed study of the possibilities offered by active and passive solar energy systems, it had been concluded that these could not be a solution in our cold climate. It had also been realized that air-to-air heat pumps, which were becoming popular in Quebec and elsewhere, also presented several drawbacks, one of which being the deterioration of the load profile.

It was then felt, however, that by coupling an active solar system with a water-to-air heat pump, it would be possible to have the best of both worlds. The heat pump would heat the house with the energy taken from a storage reservoir. Weather permitting, the sun would replenish the reservoir with energy. After a few days without sun, the temperature of the water in the reservoir would become close to the freezing point. If the heat pump could be made capable of generating ice, the amount of energy available to the

house would then become very large. Working at such a low temperature, the solar collectors would also become very efficient. The main task was then the designing of a simple and efficient ice-maker heat pump.

THE SUPERCOOLING PHENOMENON

It has been observed that phase changes are often accompanied by an "instability" by which a substance tends to keep its initial phase for temperatures well beyond phase equilibrium temperatures. Water supercooling is one of those instabilities: water stays in the liquid phase down to temperatures well below the so-called "freezing point". Actually, it seems that instead of talking about instabilities, one should rather differentiate between two different notions: the nucleation temperature (that at which an initial ice crystal is formed within the water) and the phase equilibrium temperature. For absolutely pure water, the phase equilibrium temperature really is 0 °C. The nucleation temperature, however, is not so well defined. It appears to be well below -30°C; actually, no definite limit has ever been set. Water existing in the liquid phase below the phase equilibrium temperature is said to be supercooled. The water supercooling phenomenon is well known to meteorologists: clouds are water droplets in a supercooled state at about -25 °C.

If a particle of ice, however minute, comes in contact with supercooled water, freezing will start immediately at the surface of the ice particle and will rapidly propagate until enough latent heat has been liberated to increase the water temperature to the phase equilibrium temperature, i.e. to 0 °C for pure water. The greater the supercooling, the faster the particle will grow. The ice formed from supercooled water is not of the solid type that we usually see. It is rather of the dendritic type: it grows as separate crystals having the shape of thin plates a fraction of a mm thick, sometimes as large as 20 cm^2.

While the introduction of a crystal of ice into the liquid is the only fool-proof method for initiating freezing of pure supercooled water, other methods can also be used: mechanical or thermal shocks, introduction of nucleants like silver iodide, etc. In ordinary static tap water, the multitude of impurities present act as nucleants so that the nucleation will normally occur at a temperature of about -5 °C [1].

In the case of water at rest, supercooling has been studied by a large number of researchers, mainly in connection with water pipe freezing and with water droplets in the clouds. In the case of water flowing in pipes, however, information is very scarce. Indeed, a literature survey has provided only two publications on the subject. The study most pertinent to the present work [2] concluded that it is possible to generate a metastable flow of supercooled tap water in a small diameter tube down to temperatures of about -4 °C , providing that the length to diameter ratio and the Reynolds number were well chosen. SUPERPAC is the first machine capable of generating a continuous flow of supercooled water. It is also the only ice slurry generator based on the principle of supercooling. The name SUPERPAC comes from "SUPER Pompe A Chaleur" (or super heat pump).

THE SUPERCOOLING HEAT PUMP

The main and unique characteristic of a SUPERPAC heat pump is its capability to extract energy from liquid water at any temperature, even at the so-called "freezing point". When coming out of the evaporator, the water is still in the liquid phase, at a temperature well below the phase equilibrium temperature, i.e. supercooled.

If this supercooled water is fed to a reservoir, the contact of the jet with any part of the reservoir (mechanical shock) will normally result in a phase change: water will separate into a liquid and a solid part; this will put the mixture back to 0 °C. Considering the value of the phase change energy, one can anticipate in such a mixture 1,25% in weight of solid particles per degree of supercooling.

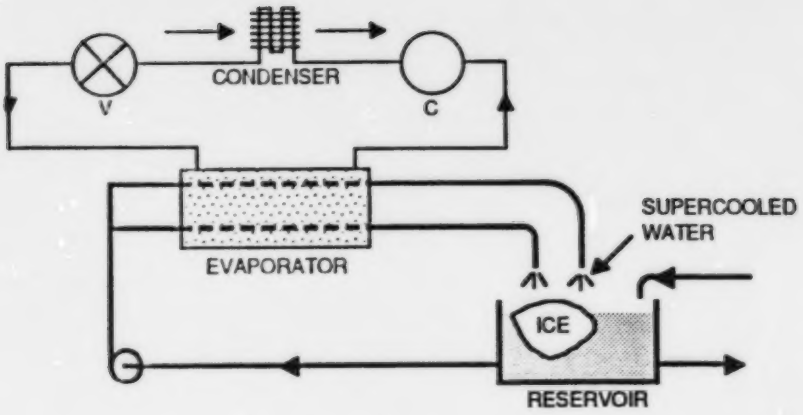

Figure 1: SUPERPAC: principle of operation.

The principle of the SUPERPAC heat pump is shown schematically in figure 1. The evaporator design will normally be of the flooded shell-and-tube type: water flows through small diameter tubes while the refrigerant is on the shell side. The phase change occurs only in the storage reservoir. The lower density ice crystals float while the liquid part goes to the bottom. The concentration of solids in the reservoir can be increased by recirculating more liquid in the evaporator.

LABORATORY TESTS

A prototype having a nominal capacity of 3 kW was built and a series of tests was performed in the EDEN Laboratory of Laval University, in Sainte-Foy, Quebec. During a typical test, the water temperatures obtained at the evaporator inlet and outlet were +0,5 °C and -1,5 °C, respectively: a stable production of ice crystals was then obtained in the reservoir. The minimum evaporator outlet temperature obtained during these tests was -2,1 °C. As the reservoir temperature went below 0,5 °C, however, evaporator freezing could not be avoided. These results were published in 1987 [3].

After an evaluation of all the preliminary tests, a certain number of possible causes were found for the freeze-up problems encountered. It was then decided to build another rig that would be capable of operating with reservoir temperatures of 0 °C. The rig comprised a 2 hp hermetic compressor fitted with a variable speed drive. The capacity could be varied from about 40% to 100% of its maximum. The evaporator had the same water tube size as the prototype, 3mm, and was installed horizontally. A heat exchanger between the hot liquid refrigerant from the condenser and the cold refrigerant vapor from the evaporator gave some superheat to the vapor before its entering into the compressor. Another optional heat exchanger between cold water from storage reservoir and hot liquid from the first heat exchanger could also be introduced in the circuit in order to make sure that the flow of cold water entering the evaporator was free of ice crystals: these crystals would induce instantaneous evaporator freeze-up.

Instrumentation was also improved: refrigerant flowmeter, wattmeter, pressure transducers and calibrated thermistors provided accurate values of mass flow, power, pressure and temperature. The machine was started and stopped via a microprocessor based controller. A new data acquisition system was also installed.

After a few weeks of preliminary testing and after many minor rig modifications, things started improving: stable supercooling was obtained, ice was generated in the reservoir, water temperatures of 0,01 °C in the storage reservoir were common and

efficiencies were quite good. Supercooling values ranging from 1 °C to 2,5 °C were normally obtained but some tests were made with liquid water outlet temperatures as low as -3,9 °C. Tests lasting more than 24 hours were made during which hundreds of kg of slush ice were fabricated. Probably for the first time ever, useful experience on the handling of supercooled water flows could be acquired. Moreover, for the first time ever, a heat pump could remove energy from liquid water at 0 °C without inducing a phase change in the evaporator. This means that such a system could be used as an all-season water-to-air heat pump.

The behaviour of the machine as an ice-slurry generator was studied very thoroughly. For example, it was found that the water-to-refrigerant heat exchanger improved the cycle efficiency but decreased the ice production rate. It was also found that compressor speed (and ice production rate) could be more than doubled without provoking evaporator freeze-up. The maximum throughput of the machine was approximately 600 kg per day. Results of these tests were published in 1989 [4] These very encouraging results confirmed the fact that this new technology could some day be commercialized. The first step in that direction was an application for patents. The next step was the construction and testing of a demonstration unit.

THE DEMONSTRATION UNIT

The 10 kW (3 ton) demonstration unit will be used to demonstrate the potential of the technology at various exhibitions. It is compact, transportable and well enough instrumented to become a valuable research tool: water and refrigerant flows, temperatures, pressures and input power can all be measured. The unit is equipped with two condensers and can thus be water cooled or air cooled, depending on the availability of cooling water. The compressor is of the scroll type: it is thus smaller, less noisy, and has better performances than conventional piston compressors. There is a refrigerant-to-refrigerant heat exchanger between condenser outlet and compressor inlet. There is also an optional water-to-refrigerant heat exchanger between the water going to the evaporator and the refrigerant going to the capillary. Its function is to improve the COP and also ensure that the flow of water to the evaporator does not contain ice crystals.

The unit is equiped with two storage reservoirs. The larger one (351 L) contains water or ice slurry. The smaller one (116 L) is used to store the ice during experiments on the separation of ice and water: water drains into the large reservoir while the ice is carried in the other one by an endless belt. The reservoirs are transparent; it is thus possible to observe the formation and movement of ice crystals below water level. A melting circuit can melt the ice when necessary. Starting the unit can be done by activating each component individually or by activating the programmable controller.

METHOD OF TESTING

Different types of tests were performed on the demonstration unit: tests of reliability, of performance and of ice properties. Different types of water were used for conducting these tests: tap water, surface water, polluted water, etc.

Reliability

The tests of reliability consisted simply in verifying if the machine could easily maintain a flow of supercooled water and produce an ice slurry during a long period of time. The procedure was simple: if after a certain running time there was no ice obstructing the water tubes, the test was considered positive. Because of the relatively small reservoir capacity, the maximum running time was about 90 minutes, after which almost all the water was converted to ice. The tests were performed using a 25 µm water filter.

Performance

Performance was evaluated by measuring or calculating five operating parameters as a function of the water temperature at the evaporator outlet:

- evaporator capacity ($\dot{Q}_L$) and coefficients of performance (COP_C and COP_t),
- mean temperature difference between water and refrigerant (ΔT_{w-f}),
- water temperature difference, between the evaporator inlet and outlet (ΔT_w).
- mass flow rate of ice ($\dot{m}_i$)

These values were calculated as follows:

$$\dot{Q}_L = \dot{m}_w \, cp_w \, \Delta T_w$$

where $\dot{m}_w$ is the mass flow rate and cp_w the specific heat of water;

$$COP_C = \dot{Q}_L / \dot{W}_C$$

where $\dot{W}_C$ is the compressor power input (kW). COP_t takes also into account the power to the water pump. ΔT_{w-f} is the difference between the (arithmetic) average water temperature in the evaporator and the refrigerant temperature.

$$\dot{m}_i = 3600 \, f_i \, \dot{m}_w \, \Delta T_S$$

where f_i is the fraction being converted from liquid to ice and ΔT_S (°C) is the degree of supercooling, defined as

$$\Delta T_S = T_{eq} - T_{wo}$$

where T_{eq} is the water equilibrum temperature and T_{wo} is the water temperature at the evaporator outlet.

All tests begin with water at 20°C in the reservoir but measurements are taken only below 15°C. This procedure allows the system to stabilize. Measurements are then taken at every degree down to 0°C and at every 0,5°C under 0°C. The volume of water in the reservoir is always above 200 liters. The water being cooled at a slow rate, all the data can be considereted constant during acquisition of a particular set of readings. The results are presented for a relatively small range of T_{wo} between -3 °C and 6 °C. The reason for that choice is the fact that above this range, the results were affected by the hot-gas bypass system, which opened automatically at 6 °C to prevent excessive condenser pressures.

Ice properties

The following ice properties were studied as a function of the working conditions: approximate texture and size, color and form of the crystals; the melted ice conductivity, which gave a good idea of its purity; and finally, the slurry equilibrium temperature. Crystal texture and size were easy to evaluate since changes were very important: crystal texture varied from very soft to really hard; crystal size varied from a fraction of a millimeter to many centimeters.

Before being melted, the crystals have to be separated from the slurry. The crystals are supposed to be pure water but the liquid water that surrounds the crystals can be more or less polluted. Two methods were used to drain the liquid water from the slurry: a gravitational and a centrifugal method. For the gravitational method, a certain volume of slurry was placed on a wire mesh during a few minutes, letting liquid water drain by gravity. The second method consisted in placing a certain volume of slurry in a semi-spherical strainer that was then spun at constant speed for several seconds. After this liquid/solid separation, the ice was melted and its conductivity measured at various time intervals: time, as will be explained later, was an important parameter.

Types of water

The types of water that have been tested are the ones most susceptible of being used in a SUPERPAC unit: tap water, salt water, polluted water, surface water (from rivers, lakes), water with an anti-corrosion additive and, finally, tap water with different degrees of filtration.

The tap water used for these tests came from the city (Ste-Foy) water-treatment system. Its source is the St-Lawrence River. It is a fairly hard water, with traces of a large number of pollutants.

The salt water tested was actually a "home-made" preparation of three different concentrations: 1,5%, 3% and 5%. This last value corresponds to the approximate salinity of the Northern mid-Atlantic ocean water. The recipe simply comprised tap water and purified NaCl. Table salt is not appropriate, since it contains many additives such as potassium iodide, inverted sugar, etc.

It would have been easy to obtain polluted water from one of the numerous polluting industries in the region (v.g. pulp and paper); but again, preparing our own recipe offered a better control on the various concentrations. Only inorganic substances were used. Local drinking water regulations were used as a guide in establishing the concentrations of "pollutants" needed. Chosen were the sulphates, nitrites, boron and iron. The maximum concentrations allowed in drinking water, for these components are, in mg/L:

- sulphate (SO_4) : 500
- iron (Fe) : 17
- nitrite (N) : 10
- boron (B) : 5

Sulphates and nitrites are not pure natural elements and are always with another element. Iron and boron are natural elements but they are not soluble in water. Sulphates were thus obtained from ammonium sulphate ($[NH_4]_2SO_4$) and ferrous sulphate ($FeSO_4.7H_2O$); iron from ferrous sulphate; the nitrites from sodium nitrite ($NaNO_2$); boron from boric acid (H_3BO_3). Table 1 shows the concentration of each substance used for each of the 5 tests. The first test, (1X), is made with 100% of the maximum allowed concentration of each of the pollutants (i.e. one time the limiting value). At each new test, the concentration was doubled (2X, 4X, etc.) and this procedure was followed until the machine was unable to run properly.

Table 1: Tests with polluted water: concentration of substances added to tap water.

	Concentrations (mg/L)				
nX the limiting value	1X	2X	4X	8X	16X
Ammonium sulphate	649	1297	2594	5188	10376
Ferrous sulphate	85	169	339	678	1355
Boric acid	29	57	114	229	458
Sodium nitrite	15	30	60	120	240

Water coming directly from a lake, a river or any natural flow of water is called "surface water". It was important to verify if SUPERPAC could work properly with this type of water, which can be a useful source of heat for a heat pump. The surface water used for these tests was taken directly from the St-Lawrence River near Ste-Foy. Chemical and physical analyses were obtained from the local water treatment plant. The main characteristic of this water is its hardness. It also contains significant traces of a large number of contaminants.

In every heating and air conditioning system, additives are added to water to avoid corrosion and scale formation in pipes. In cold water systems, the additive is often a molybdate based corrosion inhibitor. The unit was thus tested with a substance of this type added to tap water. The product used was the Dearborn 545, (by Dearborn Chemical Co.) at the specified concentration of 0,3 % by volume.

It is well known that particles in suspension in supercooled water can initiate the crystalization process. Such a situation should obviously be prevented in a SUPERPAC machine. Some means of filtering the reservoir water before its entrance in the evaporator should thus be installed. How thorough the filtration should be is not well known, however. Tests were thus conducted with 5, 25, and 50 microns filters.

ANALYSIS OF RESULTS

Reliability

Tests were performed for each type of water mentioned above. All were completely positive except for the case of the extremely polluted water. In the tap water case, the tests were repeated 3 times. The unit performed perfectly each time, until practically all the liquid had been transformed to ice. Actually, the tests went like this: with water at about 1,5 °C in the reservoir, the unit was started. The flow rate of water through the system was set at about 1 L/s. After about 75 minutes, most of the liquid would be converted to ice, so much so that the flow through the pump would start to drop sharply. The whole unit would automatically stop at a flow of 0,35 L/s. The operator would let the liquid water drain and accumulate at the bottom of the reservoir for 5 minutes and then restart the unit manually. The machine would then operate for a few minutes and stop automatically again for the same reason as before. This procedure was repeated 4 or 5 times until practically no liquid water was left. As mentioned above, this whole procedure was repeated 3 times. During all the tests, none of the tubes froze, even during the periods of very low flows.

For the other types of water, only one complete test was performed. With surface water, salt water and with tap water plus an additive, the unit operated just as reliably as with tap water alone. As will be explained later, however, important differences were observed in the texture of the ice crystals generated from salt water.

With polluted water, the machine ran perfectly for the first four tests, i.e. up to concentration values of 8X. The only problem came from the fact that the 25 µm filter would get saturated and the water flow rate would drop slowly. At a 16X concentration, however, the tubes began to freeze. After 45 minutes of operation, most of the tubes would plug up. It is probable that at this high concentration, one or more of the components in the solution started precipitating, which provoked freezing in the affected tubes. It should be mentioned here that even at the 8X concentration, the turbidity was so high that one could not see through 30 cm of that water. Two reliability tests were also performed with 5 and 50 µm filters. No difference in the results could be detected. Tests with 200 µm filters are planned. It should also be mentioned that the unit has often been operated successfully for long periods of time without any water filtering.

Performance

The test results obtained with tap water are shown in figures 2 to 4. Figure 2 shows the evaporator capacity $\dot{Q}_L$ and the coefficients of performance. The capacity decreases with T_{wo}, as could be expected, but it levels off below 0 °C, which is quite surprising. This peculiar behaviour below 0 °C was a constant for all the tests. No really convincing explanation could be found for the phenomenon. There is a feeling that it could be related to the presence in the circuit of the water-to-refrigerant heat exchanger.

Capacity and compressor input power increasing at about the same rate with T_{wo}, the COP_C curve is almost flat at a value of about 3,2 for the whole temperature range shown. The exact value of the global coefficient of performance COP_t is not particularly significant since it contains the pumping power which, here, is relatively high. This is due to the small internal diameter of the water tubes, 3 mm. In a commercial machine, the internal diameter would be 9 mm or more, which would decrease the pressure losses and the pumping power considerably.

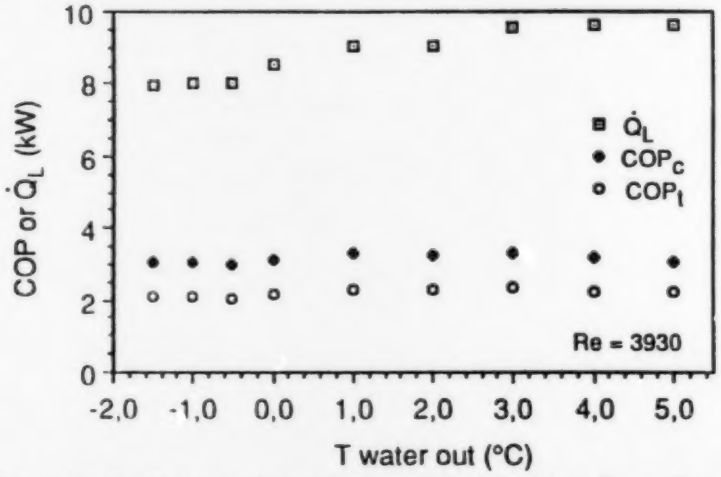

Figure 2: Coefficients of performance and capacity vs T_{wo}. Tap water.

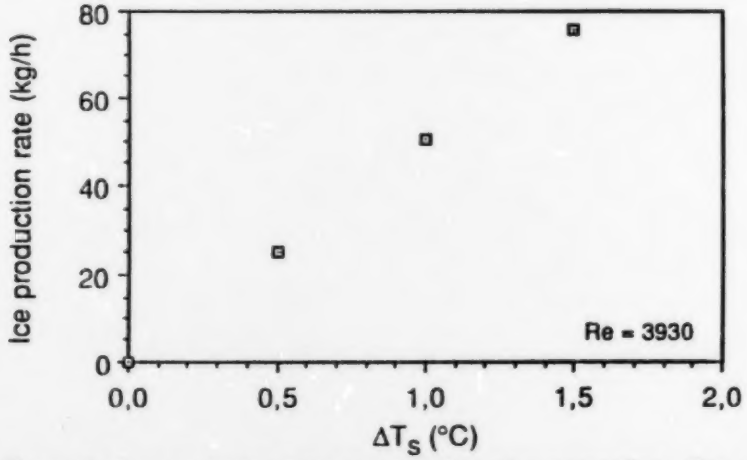

Figure 3: Ice production rate as a function of supercooling. Tap water.

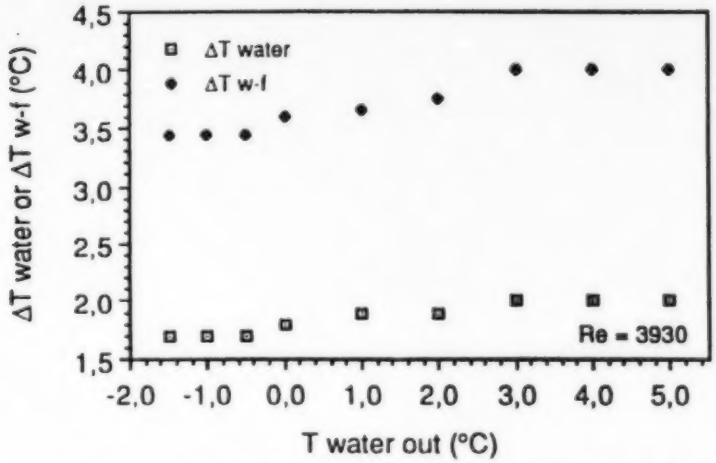

Figure 4: Water ΔT across the evaporator and ΔT between water and refrigerant as a function of Two. Tap water.

Figure 3 shows that the ice production rate increases with the supercooling of the water, ΔT_S. With a supercooling of 1,5°C, the production rate is 75,5 kg/h, which corresponds to a little more than 1,8 tons per day (t/d). During this test, the maximum supercooling was 1,7°C, with a corresponding rate of production of about 2,1 t/d. At that moment, the Reynolds number was equal to 3900.

Figure 4 shows the variation of the ΔT across the evaporator (ΔT_{water}) and of the ΔT between water and refrigerant (ΔT_{w-f}) as a function of T_{wo}. There again, it can be seen that these two parameters tend to level off below 0 °C. It is also interesting to note that ΔT_{w-f} decreases with temperature and is at a minimum during the ice production process, i.e. below 0 °C.

The performance with surface water and with tap water plus additives was practically identical to the one for tap water shown in figures 2 to 4. For polluted water, the results were also very similar, as shown in figure 5 giving the ice production rate. The scatter in the results can be explained by the fact that it was difficult to adjust the water flow rate because of the relatively rapid saturation of the filter due to the large amount of impurities in the water.

Obtaining accurate performance results with salt water is more difficult than with tap or surface water. A corrected value for the heat of fusion and for the specific heat should be used in the calculations. Moreover, the turbine flowmeter should be recalibrated. None of that was done here, for lack of time. Only raw values are thus given here.

Figure 6 shows the variation of the capacity and the COP as a function of T_{wo}. Again, the capacity levels off between 0 °C and -2 °C. It starts going down again below -2°C. The COP values are again almost flat over the whole range, except below -2 °C. It should be mentioned that the minimum value of T_{wo} here is -3,5 °C. This corresponds to a ΔT_S of 0,5 °C only, since the equilibrium temperature was -3 °C. At the Reynolds number of the tests, the unit could not give a lower value of T_{wo}. At this low value of ΔT_S, the ice production rate was of course quite small.

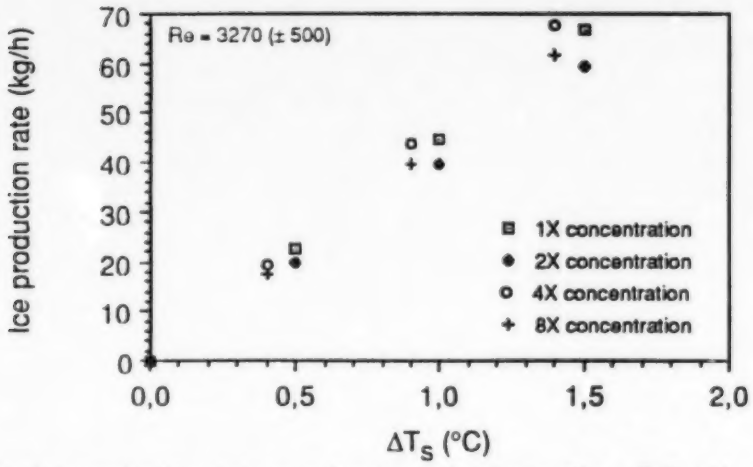

Figure 5: Ice production rate as a function of supercooling. Polluted water. Impurities concentration: 1 to 8 time the allowed value.

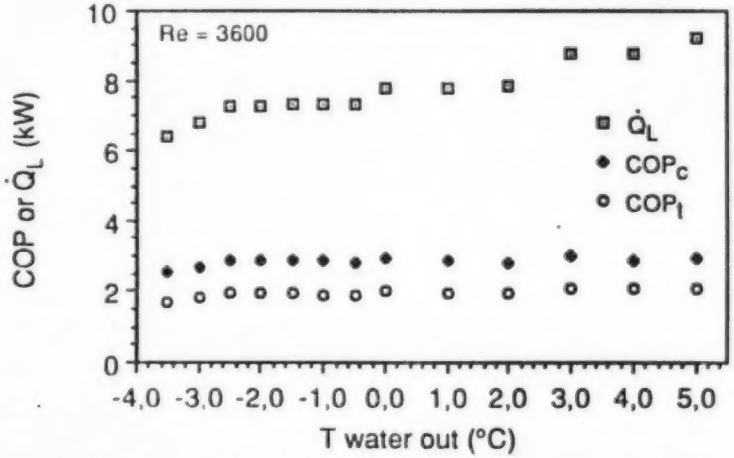

Figure 6: Coefficients of performance and capacity vs T_{wo}. Salt water. Salinity: 5%.

Ice properties.

The physical properties of individual crystals depended both on the conditions of operation and on the type of water used. For example, with salt water, it was possible to produce crystals that were so fine that a 30% solid slurry, when manipulated with the hand, would behave just like water. A larger concentration of salt in the water would increase that effect considerably: indeed, it was very difficult to produce crystals larger than about 1 mm with salt water having a concentration of 3% and higher.

With tap water, surface water and slightly polluted water (up to about 2X), almost complete control over the size of the crystals could be obtained by varying operating conditions. Sizes ranging from a small fraction of a mm to stalagmites shaped crystals of several cm could easily be obtained. Actually, it was even possible to manufacture large blocs of hard, solid ice with a mass of several kg. Water with a low salt concentration or with a higher concentration of pollutants behaved somewhere in between those two above described extremes.

The phase equilibrium temperatures T_{eq} for the 3 concentrations of salt water solutions tested went from -0,4 °C to -3 °C. For the 5 concentrations of polluted water solutions tested, T_{eq} went from 0 °C to -0,4 °C.

Because of the presence of the dissolved iron in the "polluted water", there was an orange tint to it that became darker as the concentration of impurities increased. It is interesting to note that the melted ice did not have that hue, no matter what the original concentration of iron was.

As already mentioned, the ice crystals are supposed to be pure water, but the liquid water that surrounds them can be more or less polluted. So it was interesting to study how easy or how difficult it was to clean the crystals. Our study was not very thorough but it indicated such a task is not an easy one. That type of study is important if one wants to design water purification systems based on the liquid-solid phase change. The liquid water can be removed from the slurry in various ways: by washing, by draining, etc. The latter method was experimented here. As already mentioned, two draining methods were tried: gravitational and centrifugal. One easy way to verify if these methods are efficient is to melt the drained ice and measure the electrical conductivity of the resulting liquid.

Without trying to present all the results, it is interesting to look at figures 7 and 8, giving the results of the conductivity measurements for the case of polluted water. As already mentioned, time played an important role in the final results: in general, the longer the ice slurry stayed at rest in the reservoir before the draining and melting process was performed, the lower the final measured conductivity. This type of result is apparent in figure 7, which shows the measured values for the case of the 8X concentration. The original solution had a conductivity of 5,5 mS/cm. Measurements made after a 3 h period show approximate reductions of 50% in conductivity with gravity draining and 72% with centrifugal draining. After 22 hours, the results were respectively 82% and 87% instead.

Figure 8 shows the results of similar tests performed with less polluted water (2X concentration). From an original conductivity of 1,6 mS/cm, it was possible to obtain a final conductivity value in the order of 0,2 mS/cm with our crude centrifugal draining method. That final value is less than the average conductivity of the Ste-Foy drinking water. What this means is that potable water can be obtained from very polluted water by going through two passes in a SUPERPAC machine, even when the crystal cleaning process is very crude. An improved cleaning process would most probably result in a much better end result and one pass would then be sufficient.

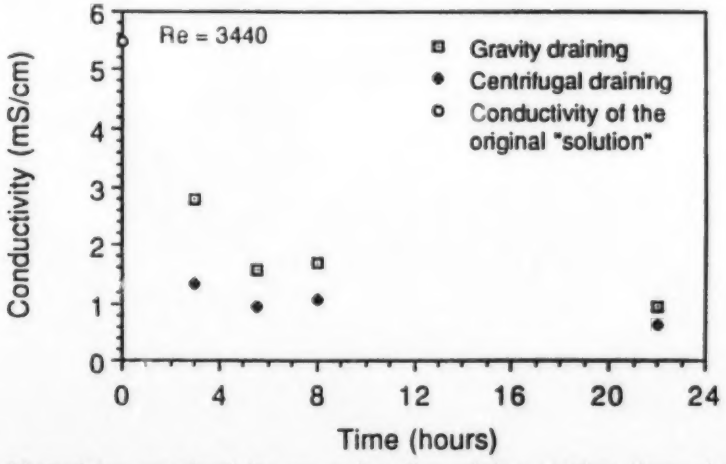

Figure 7: Melted ice conductivity as a function of the resting time of the slurry in the reservoir. Polluted water. 8X concentration.

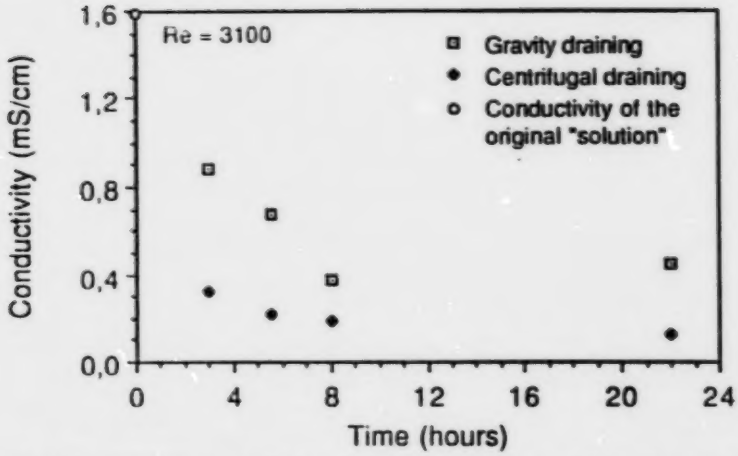

Figure 8: Melted ice conductivity as a function of the resting time of the slurry in the reservoir. Polluted water. 2X concentration.

The importance of the time factor warrants some comment. A plausible explanation is that the resting time is used for crystal reorganization, small crystals regrouping themselves to form bigger ones. Bigger crystals being easier to clean, liquid water draining more easily, the resulting melted ice has a lower conductivity. The available equipment did not permit a verification of this assumption.

ONGOING EXPERIMENTS

Tests are now under way to expand the sum of knowledge on the supercooling phenomenon and to study the possibility of using the SUPERPAC technology in a full size district heating or cooling system. For example, tests are being performed with 9 mm i.d. water tubes at a larger range of Reynolds numbers than previously possible: from 1000 to more than 10 000. Preliminary results are excellent. Tests on larger diameter tubes (up to 15 mm i.d.) will soon be under way . These are the types of tube sizes that will be used in full size machines.

APPLICATIONS OF THE TECHNOLOGY

When completely developed, the SUPERPAC technology will have a large number of applications, particularly in the fields of district heating and cooling and of energy management. These are fields where the SUPERPAC technology can be very beneficial. These are also fields where almost everything remains to be done, at least in North America. Indeed a comparative study of heating and cooling methods in America and Europe readily shows that the American approach is more conservative. On our continent, inertia is enormous. The fact that the U.S.A. is still debating on the merits of an energy policy is very revealing. In Canada, much still remains to be done. On the positive side, however, this also means that the potential for improvement is enormous.

Heating

Figure 9 shows an application having a vast potential in the residential, the commercial as well as in the district heating field: a full-range water-to-air heat pump. The energy source is a lake or the sea. Contrary to conventional systems, the heat pump here is operable even when the lake is partly frozen and the water is at the so-called freezing point. The supercooled water coming out of the machine is simply returned to the large body of

water. No back-up system is necessary. In northern European countries where district heating systems sometimes use the North Sea water as a heat source, heat pumps have to be shut down for two or three months, when sea water becomes too cold. Oil is then used as a source of heat. A SUPERPAC heat pump would be operable all winter and save important quantities of oil.

Cooling with ice slurries

Figure 10 shows another application in the field of air conditioning. The energy transport fluid circulating in the heat exchanger can either be the cold water from the bottom of the reservoir or the ice slurry from the top. Tests have been reported in the literature showing that ice slurries with 20% or more of solid particles could easily be circulated in pipes, pumps and heat exchangers. Compared to conventional chillers, ice-slurry systems have a number of well known advantages, one of which is the possibility for cold side energy storage and energy management. Figure 11 shows an application where one central ice-slurry generator is used to cool two or more buildings. There is one small slurry reservoir near the generator and other local storage reservoirs, one in each building. The advantages of such a system are important:

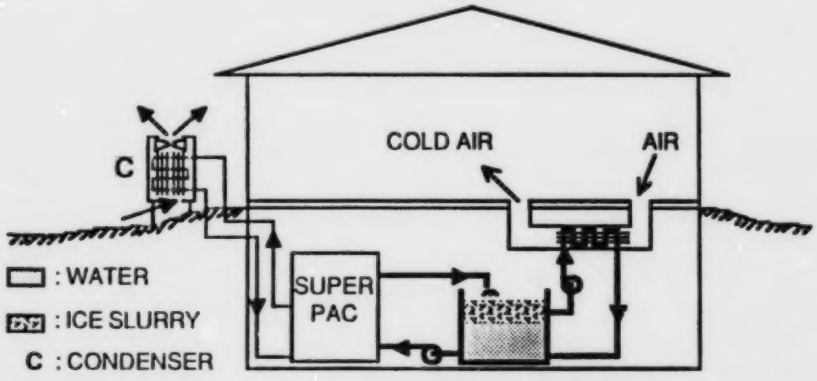

Figure 9: Air conditioning with SUPERPAC.

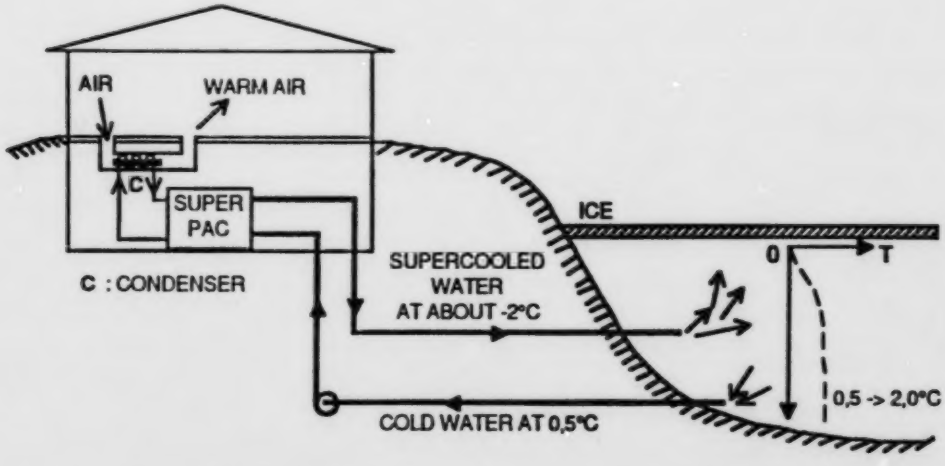

Figure 10: SUPERPAC as a full-range water-to-air heat pump.

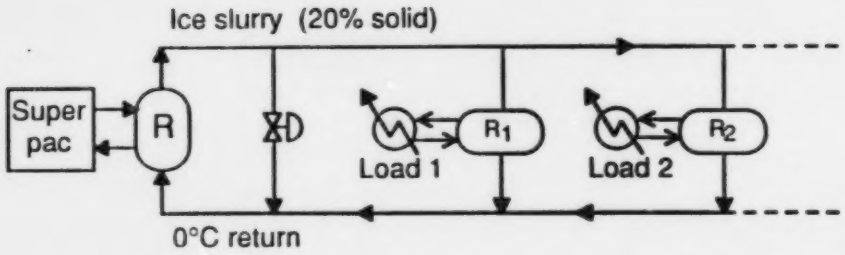

Figure 11: District cooling with SUPERPAC (local storage).

- the mass flow rate in the main pipe is small, which translates in smaller pipe sizes, lower pumping power and important energy savings

- elimination of large peak loads and a lower capacity of the cooling plant

These advantages are also offered by the other ice slurry technologies. The SUPERPAC technology, however, offers several other very unique advantages:

- it can operate with pure water. This is not the case for the binary solution ice-slurry generators; salt or glycol must then be added to the water to prevent freeze-up.

- there is no potential for environmental problems, as with the direct contact method where the ice slurry circulating in the piping system will always contain traces of refrigerant: a water leak in the system would then negatively affect the environment.

- its design is simple. Being an indirect contact system, it can incorporate "off the shelf" condensing units. The only differences lie in the evaporator design and in the way the water is handled before and after its passage through the cooling system. The evaporator is of a modified flooded shell-and-tube design and its construction is well within the capabilities of any good heat exchanger maker.

- it is as easily upscaled as any water chilling system. Small units making 20 kg of ice per day or large units making 2 000 tons per day are possible. Upscaling only implies multiplying the number of water tubes inside the evaporator.

It should also be realized that the cold side storage capability is not advantageous only in new installations; existing conventional systems can also be fitted with ice storage.

Cooling with very cold water

One can imagine a case where the capacity of an existing chilling system is to become insufficient, an important increase in load being anticipated. An ice-slurry generator might not be necessary, however, since the SUPERPAC technology can also provide full-range chillers capable of generating water flows at any temperature between 7 °C and 0 °C. Since, in this example, the installed chiller already gives water at, say, 7 °C, a SUPERPAC chiller installed in series could give a final temperature of 4 °C. This would provide a 50% increase in capacity. Another chiller could be added in series later, for a final oulet temperature of 1 °C and a total increase of 100% in capacity, all of that being achieved without any change to the size of the main water line. If another increase in capacity should ever become necessary, the SUPERPAC ice-slurry generating capability could be used: another doubling in capacity could thus be obtained.

CONCLUSION

A new technology has been developed capable of generating very low temperature liquid water flows, down to the supercooled state i.e. well below the so-called freezing point. From this supercooled state, ice slurries can easily be generated. Previous laboratory experiments have shown that heat pumps based on this technology were not an unrealistic dream. Current tests are showing that large scale machines can also be built.

The present paper has presented the results of a series of tests performed on a transportable demonstration unit capable of generating 2 tons of ice per day. The machine has been found to be reliable, capable of working with just about any type of water. The size of the ice crystals generated could be controlled at will: from the small crystals having the look and feel of wet snow to the large hard crystals several cm in length. The performance of the machine was comparable, if not superior, to other machines of the same size and of the same temperature range.

Applications of this technology in the fields of heating, cooling and energy management were briefly explained. Its potential use in the field of water treatment was also hinted at. The technology, however, has applications in several other fields like agriculture, fishing, construction, snowmaking, etc.

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